Nanotechnology: Thinking Small

Nanotechnology—building devices on the atomic scale—may unleash some big scientific advances early in the new millennium. Last January in Arlington, Virginia, nearly 100 representatives from academia, industry, and government laid out the general goals for the next decade of nanotechnology research by U.S. government agencies. Some predict that the potentially rich opportunities in this field may trigger a nanotechnology initiative in the federal budget request for Fiscal Year 2001. In the meantime, Congress has asked the NIEHS to explore how nanotechnology might be used to address environmental heath problems.

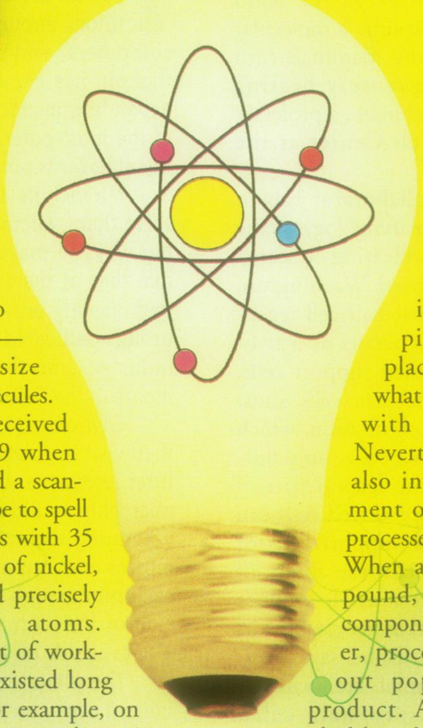
Sheila Newton, director of the NIEHS Office of Policy, Planning, and Evaluation, says, "The [NIEHS] has been considering possible uses for nanotechnology in environmental health science ever since the first mention of nanofabrication appeared in the House Appropriations report language for Fiscal Year 1997. That item encouraged the NIEHS to explore the possibilities of nanotechnology for improving the detection, prevention, and remediation of environmentally related illnesses. While we are still only beginning to tap that potential, we now have some initiatives under development that will open some opportunities for us."

According to Newton, the NIEHS has been an active player in a National Institutes of Health effort to develop a bioengineering initiative, of which nanotechnology is an important part. The first two multi-institute bioengineering requests for grants applications were released this year and include NIEHS participation. Says Newton, "The initial and future rounds of these [requests for applications] will provide a useful framework for funding of nanotechnology research." Other program areas with potential for development of environmentally related nanotechnologies, says Newton, are the Small Business Innovative Research Program and the Superfund Basic Research Program.

Not Just Small Talk

In general, nanotechnology means building something by manipulating the placement of pieces that vary in size from 0.1 to 100 nanometers (nm)—roughly the range of size between atoms and molecules. Nanotechnology first received broad attention in 1989 when investigators at IBM used a scanning tunneling microscope to spell out the company's initials with 35 xenon atoms on a piece of nickel, showing that they could precisely position individual atoms. Nevertheless, the concept of working in the nano-range existed long before IBM's success. For example, on 29 December 1959 at the annual meeting of the American Physical Society, the late physicist Richard Feynman, then at the California Institute of Technology, delivered a talk titled "There's Plenty of Room at the Bottom" in which he said that "the principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom. It is not an attempt to violate any laws; it is something, in principle, that can be done, but in practice it has not been done because we are too big." Many scientists have surely noted that nature already uses its own form of nanotechnology, for instance in building the biochemical "factory" that runs photosynthesis or in carrying out the process of DNA replication. Although nature holds millions of years of experience in nanotechnology, this realm is an entirely new world to human technology.

Nanotechnology means more than making a smaller version of something. It can mean making something entirely new, something with unheard-of properties, because a material's characteristics can change dramatically depending on the organization of atoms. For example, consider pure carbon: one organization of carbon atoms produces graphite and another produces diamond.



In some cases, nanotechnology may involve building things one atom at a time. Investigators could, say, use an atomic-force microscope to pick up one atom and place it just so, similar to what the IBM researchers did with the xenon atoms. Nevertheless, nanotechnology also involves the mass movement of many atoms through processes such as self-assembly. When a chemist creates a compound, for instance, all of the components are dumped together, processed in some way, and out pops the desired final product. A similar process will probably be used in many nanotechnology applications.

It's a Small World After All

A variety of environmental health applications seem promising. Newton says, "Detection technologies are of particular relevance to NIEHS goals in environmental public health and represent some of the areas of greatest potential impact for nanotechnology." For example, she points to the work of chemist Raoul Kopelman of the University of Michigan at Ann Arbor. On his Web site located at **http://www.umich.edu/~michchem/faculty/kopelman/**, he writes, "Our group has produced the world's smallest light sources and the smallest and fastest fiber-optic chemical sensors. This enables optical, spectral, and chemical imaging on a nanometer scale."

The sensors developed by Kopelman were recently used by NIEHS grantee Martin Philbert, a chemist in the University of Michigan's Department of Environmental and Industrial Health, to measure the neurotoxicant-dependent release of minute quantities of calcium ions from the permeability transition pore of mitochondria. This example of dynamic physiological measurement suggests that other sensors might be used to very accurately monitor other physiological processes inside a cell in response to other toxicants. From that, one might eventually find a correlation between such physiological effects and a disease caused by an environmental factor.

The most recent NIEHS-supported conceptual developments in nanotechnology have come from Melvin Billingsley, a professor of pharmacology at the Pennsylvania State University College of Medicine in Hershey, who plans to collaborate with Kopelman and Philbert on the design and production of sensors with intracellular targeting capabilities. Such sensors will be able to monitor environments immediately proximal to the cellular targets of environmental toxicants.

Other aspects of nanotechnology might also benefit environmental health. For example, Ralph C. Merkle, a research scientist at the Xerox Palo Alto Research Center in California and a noted authority on nanotechnology, says, "Several conclusions stand out about environmental implications. First, molecular nanotechnology is a very precise manufacturing technology, hence very clean. Current manufacturing technologies produce pollutants, not because manufacturers want to pollute but because the manufacturing process is imprecise and uncontrolled. A precise manufacturing technology won't pollute. [For example], it might produce sulfur, but it won't send sulfur up the smokestack in some random, undesired molecular form. Instead, it might make bricks of sulfur that could be sold." Merkle goes on to say that nanotechnology could also reduce the levels of pollution created in agriculture and mining by leading to more efficient production of food and development of new forms of energy, respectively.

In other potential environmental health applications, materials with nano-size pores could be used as filters to remove contaminants. In 1992, Mobil Oil Corporation announced the creation of a family of aluminosilicates that could be made with atoms packed in an orderly manner to create consistent, tiny pores. One of these materials, Mobil crystalline material 41 (MCM-41), allows consistent pores to be created in the size range of 2–19 nm in diameter. Many laboratories are experimenting with this material.

Jun Liu, a staff scientist in colloids and materials design at the Pacific Northwest National Laboratory in Richland, Washington, says, "Ordered nanoporous ceramic substrates have been developed with controlled shapes and sizes to serve as efficient traps for specific environmental and chemical pollutants. The key lies in the ability to control the nanoporosity and to tailor the surface chemistry to the pollutants, whether they are heavy metals, transition metals, or organic materials." Materials can be created with pores of the proper size and coated with appropriate materials to capture specific pollutants. Liu explains, "During the processing, oriented organic molecular monolayers are attached to the nanopores. The materials forming monolayers are selected to recognize a specific class of pollutants and serve as their hosts. Spectroscopic characterization and computer modeling indicate that the monolayers are closely packed to near-theoretical density [nearly as tight as they could possibly be] and tightly bonded, within a few angstroms, to one another and to the substrate."

Chunshan Song, director of the Applied Catalysis in Energy Laboratory at Pennsylvania State University in University Park, and his colleagues use MCM-41 to create what he calls environmentally friendly fuels by removing troublesome components. "Our research group has synthesized and applied mesoporous aluminosilicate molecular sieve MCM-41 as support of two types of catalysts for deep removal of sulfur, which is responsible for black smoke, and polyaromatic compounds from diesel fuels," he says. To remove sulfur from fuel, Song says, a highly active catalyst can be prepared by loading proper amounts of cobalt and molybdenum onto Al-MCM-41.

Big Potential for Little Chips

A form of nanotechnology used to create so-called DNA chips holds the potential to solve many environmental health research problems. Nanotechnology is used to attach pieces of DNA called oligonucleotides, or cDNAs, to a glass chip, filter membrane, plastic, or some other material. As many as 100–1,000 different DNA sequences, which act as probes, can be attached in a checkerboard pattern. When a test solution is exposed to the chip during a hybridization assay, segments of DNA in the test solution will bind to the chip if they are complementary to DNA probes present on it. Matching the hybridization site pattern to known DNA patterns reveals the sequence or expression level of the unknown DNA from the test solution.

NIEHS scientific director J. Carl Barrett and his colleagues in the Laboratory of Molecular Carcinogenesis have developed a DNA chip called the ToxChip [see *EHP* 107(5):A256–A258 (1999)]. With this DNA chip, investigators can look for changes in gene expression for thousands of genes when they are exposed to various chemicals. Cynthia A. Afshari, a staff scientist working on the project, says, "The ToxChip will be used mostly to identify the mechanisms of actions and to categorize potentially harmful agents." For example, it could be used to measure the toxic effects of a compound in a biological system or to help identify the cause of certain environmentally related diseases.

Fred Brockman, a staff scientist in environmental microbiology at the Pacific Northwest National Laboratory, hopes to use a DNA chip to identify microorganisms. He says, "If one is using a DNA chip with probes specific for all kinds of different bioremediative organisms or other microorganisms known to exist in the environment, then the chip can be used to analyze the structure of the community and how it changes over time as a result of a bioremediative process or as a result of environmental insults."

Nevertheless, a DNA chip will not work very well on an ordinary sample of certain materials (for instance, soil). "There are lots of exquisite detectors, chips being just one of them," Brockman says. "But if you do not present the detector with a very highly purified . . . and highly concentrated sample, it simply cannot do the work it was designed to do." Consequently, Brockman and his colleagues have spent two years developing an automated process to clean up what he calls "dirty" samples—sediment, high-volume aerosol samples, meat homogenates, and food rinsates—so they can be tested with a DNA chip. "We have developed a bead-based flow-through system that purifies DNA and RNA from these types of samples," he says.

In February 1999, the French companies Lyonnaise des Eaux and bioMérieux announced a DNA chip that monitors drinking water quality. According to company literature, this device "will permit the detection of lower concentrations of microorganisms in the water and the accurate identification of many types of water contaminants." The developers also claim that this device will cut testing time from a current average of 48 hours to just 4 hours. This device relies on the GeneChip technology developed by Affymetrix [see *EHP* 103(3):244–246 (1995)].

Although nanotechnology is just emerging, it already provides previously unheard-of capabilities, and many more seem sure to follow. The NIEHS and other organizations are continuing to explore the promise of nanotechnology research to make big improvements in environmental health by working on a very small scale.

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